

Performance analysis and electronics packaging of the Optical Communications Demonstrator

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ABSTRACT

The Optical Communications Demonstrator (OCD), under development at the Jet Propulsion Laboratory (JPL), is a laboratory-based lasercomm terminal designed to validate several key technologies, primarily precision beam pointing, high bandwidth tracking, and beacon acquisition. The novelty of the instrument is that it uses a single CCD array detector for both beacon acquisition and tracking, and a fiber-coupled laser transmitter. The resulting reduction in design complexity can lead to a reduced system cost and an improved system reliability. In this paper, we describe recent progress on the development of the OCD terminal, particularly the electronics packaging and optical characterization with the Lasercom Test and Evaluation Station (LTES).

Keywords: Optical Communications, Laser Communications, Beacon Acquisition, Tracking, Free-space, LEO, GEO, OCD

1. INTRODUCTION

The greatest advantage of laser communications over RF for space-to-ground communications, namely narrow beamwidth, also poses the most technical challenge. The considerably smaller transmit beamwidth, typically on the order of tens of microradians, imposes stringent demands on the pointing system in the presence of spacecraft vibration. Inaccurate beam pointing can result in significant signal fades at the receiving site resulting in a large number of burst errors. Thus, one of the important steps in realizing space-ground laser communications is to track the target (or receiver) with residual pointing error that is small compared to the transmit beamwidth.

The Optical Communications Demonstrator (OCD) program at JPL was created to demonstrate in a laboratory environment several key free-space lasercomm technologies, primarily precision beam pointing, high bandwidth tracking and beacon acquisition. The OCD terminal, designed and constructed over the last few years, uses a reduced complexity architecture. In this patented architecture only one fast steering mirror (FSM) and one detector array are used for all acquisition, tracking and point-ahead functions [1]. The large field-of-view (FOV) array detector is used in a "windowed" mode for achieving high frame rates that are required in the tracking mode. Since OCD was designed mainly for dumping data from LEO/GEO orbit at very high rates (100 Mbps to several Gbps), there is no communications detector on the terminal. This reduction in the number of components is expected to increase system reliability.

The OCD consists of several components - the telescope optics assembly (TOA), a gimbal for coarse pointing, a fiber-coupled laser transmitter, and electronics to control and operate the terminal. The TOA, consisting of a 10-cm telescope, an array detector, a two-axis fine steering mirror, and miscellaneous opto-mechanical components, is mounted on a gimbal. The transmit laser is located away from the telescope, and is coupled to the TOA using a single mode optical fiber. The fiber coupled laser transmitter eases thermal management issues, and makes it easy to put in a different laser. Though some of the electronics for the CCD are mounted on the TOA itself, most of the electronics (including the processor) are placed away from the TOA and gimbal. Table 1 lists the major components of the OCD, their manufacturer and model, and some specifications. Detailed descriptions of the OCD design and the choice of components can be found in Refs. [2,3].

The TOA has been designed, constructed and assembled. A gimbal was procured and tested just over a year ago. Proof-of-concept electronics hardware and software were developed on a separate test bench to validate the high bandwidth CCD-based tracking concept. In the past few months the assembled OCD was integrated with the electronic hardware and software and co-aligned with the Lasercomm Test and Evaluation System (LTES). LTES

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Table 1. Major components in OCD

Item	Manufacturer/Model	Specs and notes
CCD	DALSA CA-D1 Modified by 20/20 Designs	128 x 128 pixel array 16 um x 16 um pixel size
FSM	General Scanning Two-axis Beam Steerer (TABS)	Voice-coil driven two-axis steerer First resonance at 17 Hz 1 in diameter, 0.25 in thick mirror No longer commercially available
Gimbal	Automated Precision Inc. (API)	Az/El gimbal with worm gear Built-in optical encoder with interpolator
Laser	SDL Inc. Model 5421	Single-mode fiber coupled 60 mW CW output power
Laser driver	Hytec Model 6110	Can be modulated to 622 Mbps

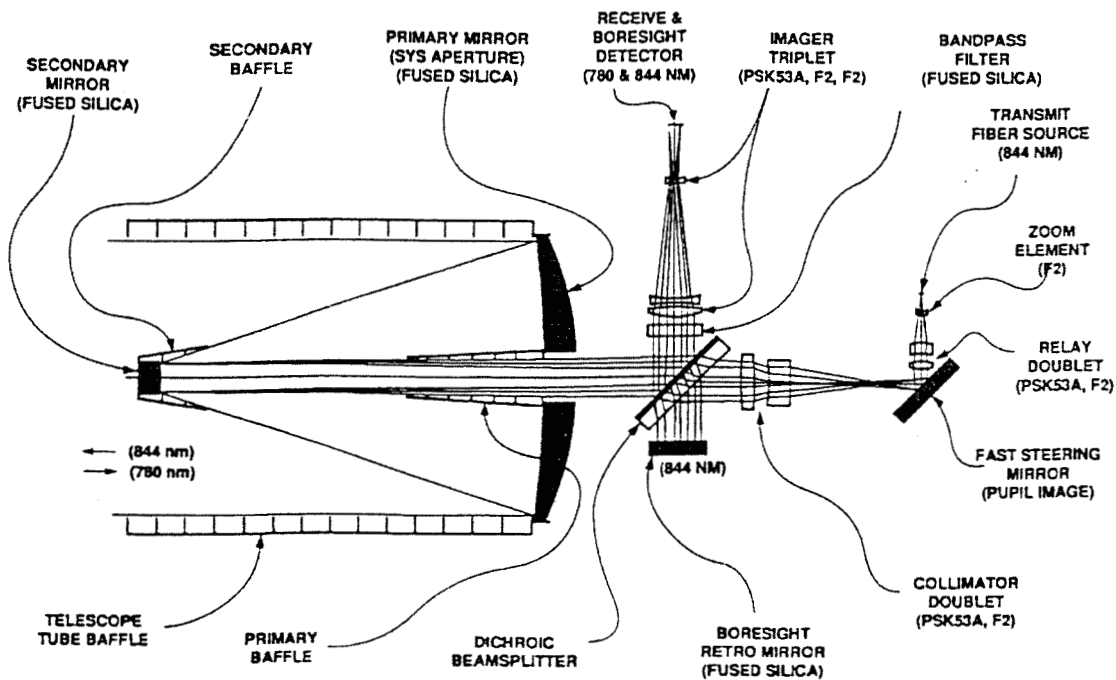


Figure 1. Optical layout of the OCD showing the transmit, receive and boresight paths.

was built at JPL as a general purpose diagnostic tool to test any optical communication terminal with aperture up to 8 inches in diameter [4,5]. In this paper we describe results of recent activities on the OCD, particularly optical characterization of the TOA using LTES and packaging of electronics into a compact unit.

2. OPTICAL AND OPTO-MECHANICAL DESIGN

As Figure 1 shows, the OCD optical assembly has three paths: a transmit channel to relay light from the laser to the output aperture through the fast steering mirror; a receive channel to relay the incoming beacon to the CCD;

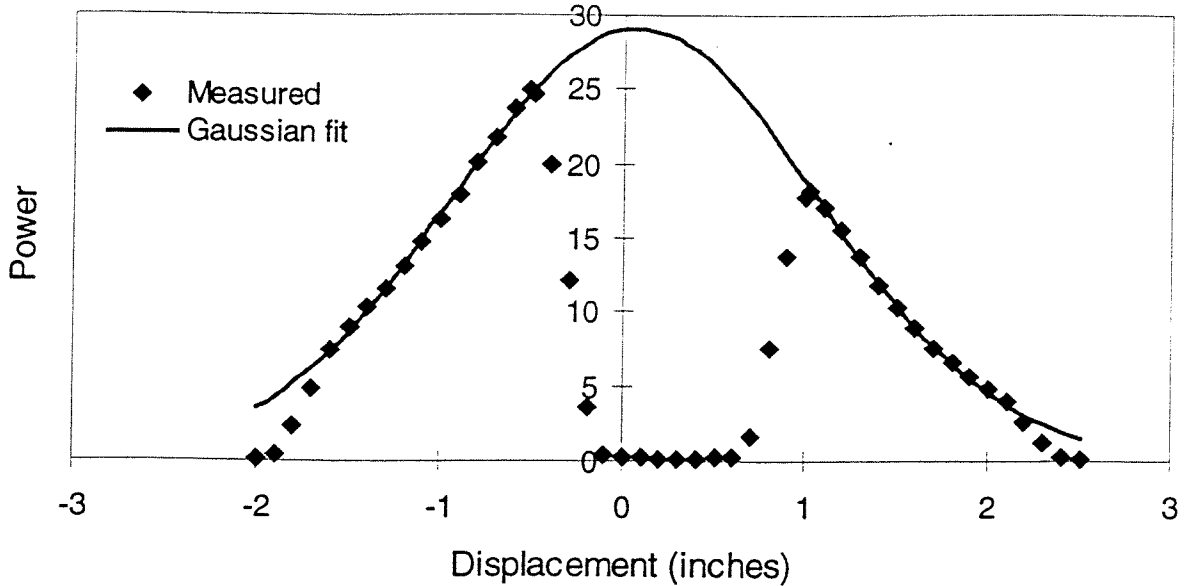


Figure 2. Intensity profile just outside the OCD telescope. Square markers are the measured data points while the solid line is the Gaussian fit. The edges are not sharp because of the large size of the detector used.

and a boresight channel which diverts part of the transmit signal to the CCD [6,7]. Since the acquisition path is not steered by the FSM, the beacon spot on the CCD moves around due to spacecraft jitter. The function of the electronics is to point the beam by controlling the FSM so that the transmit laser spot (from the boresight channel) on the CCD maintains a given vector distance from the beacon spot.

2.1. Transmit Optical Path

The 840 nm laser light from the fiber-coupled laser is expanded and collimated before it is deflected by the FSM. Nearly all the power in this beam is transmitted through a dichroic beam splitter and exits the OCD telescope aperture. Around 40% of the power from the laser is transmitted out of the telescope. This compares well to the expected value of 42%. Note that over 25% of the power is lost because of the secondary obscuration and primary truncation. The Gaussian profile of the beam from the fiber is expanded to realize optimum gain given the size of the OCD's primary and secondary as shown by Klein and Degnan [8]. Figure 2 shows the measured near-field pattern of the OCD. The Gaussian profile of the beam, size of the primary and secondary are apparent from the figure.

The observed profile of the far-field pattern, as recorded on the divergence channel of LTES, is shown in Figure 3. The observed size of the Airy disc agrees well with the predicted value of $21 \mu\text{rad}$. The observed far-field profile, however, exhibits asymmetry as well as unusually large secondary rings. In fact, only about 40% of the power exiting the TOA is in the central disc. For an Airy pattern, produced by a uniform circular field, about 68% of the energy is in the central disc when the optical system Strehl ratio is 0.8 [9]. The obscuration and the Gaussian profile of the field from the OCD is expected to slightly decrease the energy in the central disc from 68%. Better alignment between the primary and secondary is expected to improve the performance.

2.2. Receive Optical Path

The incoming beacon at 780 nm is collected by the 75 cm^2 area of the OCD telescope. Nearly all of the collected energy is reflected off the dichroic beamsplitter and passes through a narrowband optical filter which rejects the out-of-band background noise before reaching the CCD camera. Almost 65% of the collected energy gets to the array detector.

The DALSA CCD camera specifications give the noise equivalent exposure (NEE) and saturation equivalent exposure (SEE) as 15 pJ/cm^2 and 45 nJ/cm^2 , respectively. For a 2 kHz frame rate (i.e. $500 \mu\text{s}$ exposure time) and $16 \mu\text{m} \times 16 \mu\text{m}$ pixel size, we thus require about 1 nW of power at the CCD for near-saturation illumination. Note

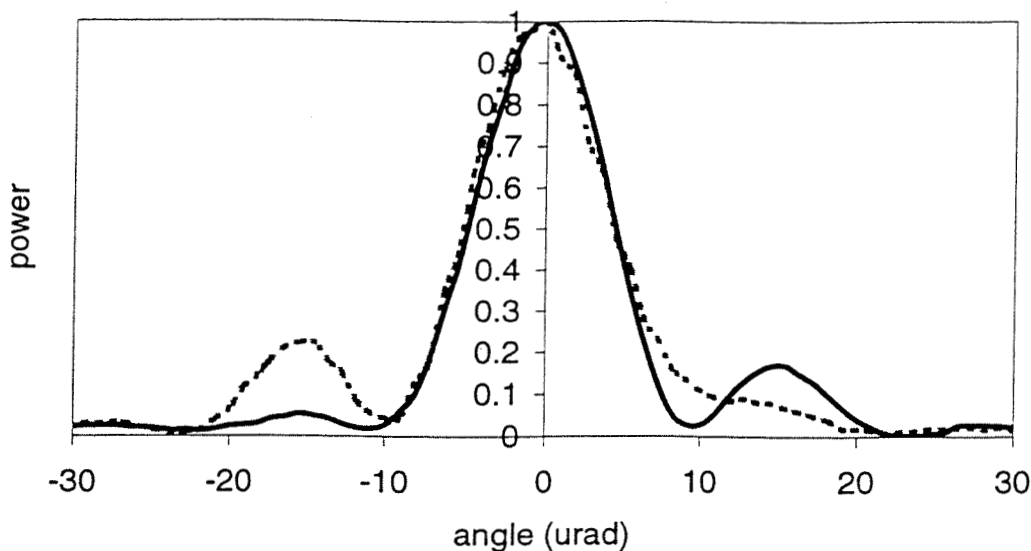


Figure 3. OCD Far-field pattern as observed in the divergence channel of LTES. The two curves are along the two orthogonal axes.

that the point spread function of the optical system results in an airy disc covering about 3×3 pixels. Typically, when the peak pixel value is near saturation, the neighbouring non-zero pixels account for about four times the peak value. Given the size of the OCD aperture and the CCD sensitivity, incident intensities in the range of 20 pW/cm^2 are needed to achieve reasonable signal-to-noise ratios for tracking purposes.

2.3. Boresight Path

The purpose of the boresight channel is to provide a real-time reference for the point-ahead angle which is accomplished by directing a fraction of the transmit beam to the CCD. A few percent of the transmit power is reflected off the dichroic beam splitter which then bounces off a “retro-mirror”. The current retro-mirror is uncoated and polished on one side, and therefore reflect about 4%. Before the 840 nm beam reaches the CCD, it is significantly attenuated by the narrow band filter (with center wavelength 780 nm and bandwidth about 10 nm). That is, only about a millionth of the transmitted power (60 dB attenuation) falls on the CCD. This is fine if the average transmit power is only about a mW. Further attenuation ($\sim 20 \text{ dB}$) is necessary in order to use a $\sim 50 \text{ mW}$ average power laser. We plan to achieve the higher attenuation in the boresight path by putting anti-reflection (AR) coating on the retro-mirror.

3. ELECTRONICS AND PACKAGING

The electronics for the OCD consist primarily of a Texas Instruments TMS420C40 (C40 for short) based DSP card and a Tracking Processor Assembly (TPA) card set. The C40 DSP card is a commercially available component and provides local data processing of camera images, and control of the fine steering mirror (FSM) and gimbal. The TPA card set is a custom built component used to interface the C40 card to the CCD, FSM, gimbal and laser. In the original design, the C40 board was a full-sized ISA card that resided in a desktop computer. The C40 card communicated with the TPA card (which was also a full-sized ISA board) through the high-speed global bus.

One of the major tasks undertaken last year was to eliminate the desktop computer and package the electronics such that the entire OCD could be made into a compact unit and interfaced to a common spacecraft bus. After some research, we found that the commercial PC/104 architecture can provide a low-cost means of reducing the size of the electronics. PC/104 is essentially a PC with a different form factor. That is, the PC and PC/104 have the same electrical signals, but the PC/104 cards are only 3.6 in by 3.3 in and have a stack-through bus [10,11]. A block

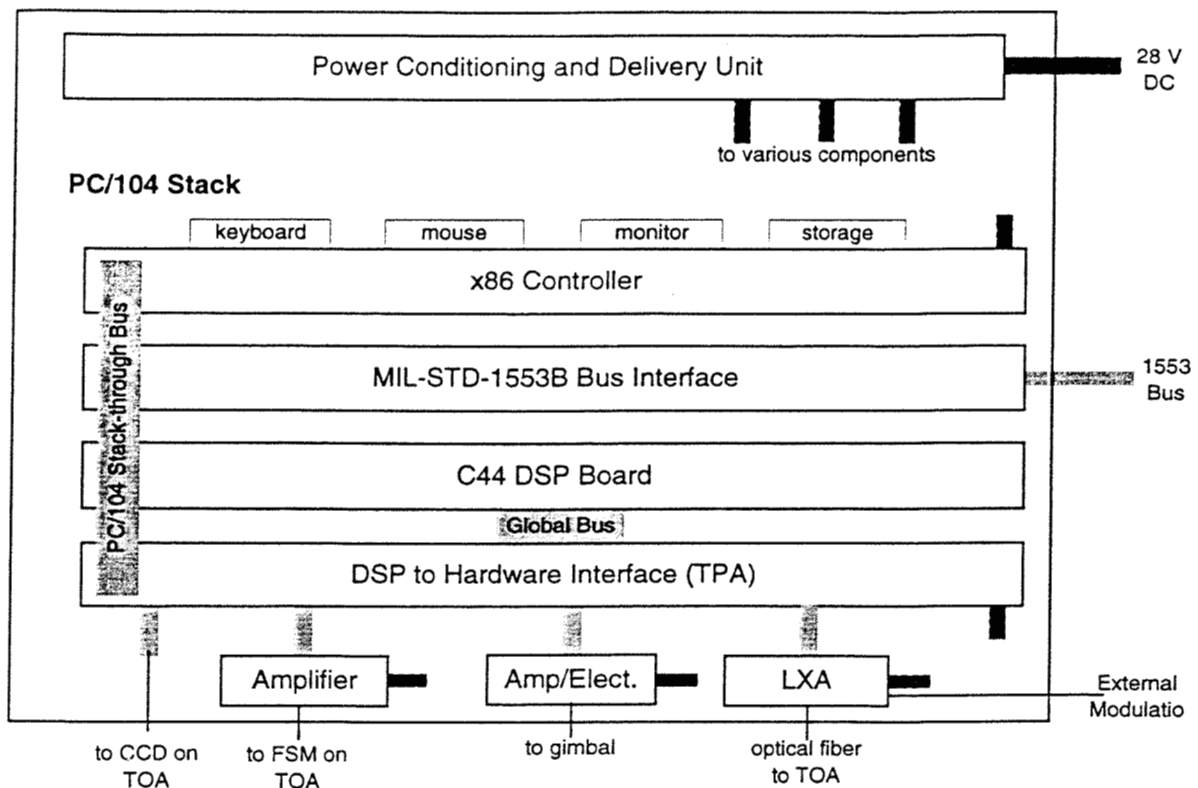


Figure 4. Block diagram of OCD electronics. The power conditioning and delivery unit consists of several DC-to-DC converters for powering the electronics from the 28 VDC source. LXA represents the laser transmitter assembly. Keyboard, mouse, monitor and storage devices can be connected to the unit during software development stage.

Table 2. Major components in OCD electronics

Item	Manufacturer/Model	Notes
Controller	Real Time Devices (RTD)	486/586 based PC/104 board 8 MB of RAM and 2 MB solid-state memory
Acq/Trk Processor	Signalogic SigC44	TI C44 based PC/104 DSP card With high-speed global bus interface
Hardware Interface	Custom made at JPL	Address decoding logic, DACs for FSM and gimbal control, and gimbal position counters
Interface	Condor Engineering MS1553PC104	MIL-STD-1553B PC/104 card

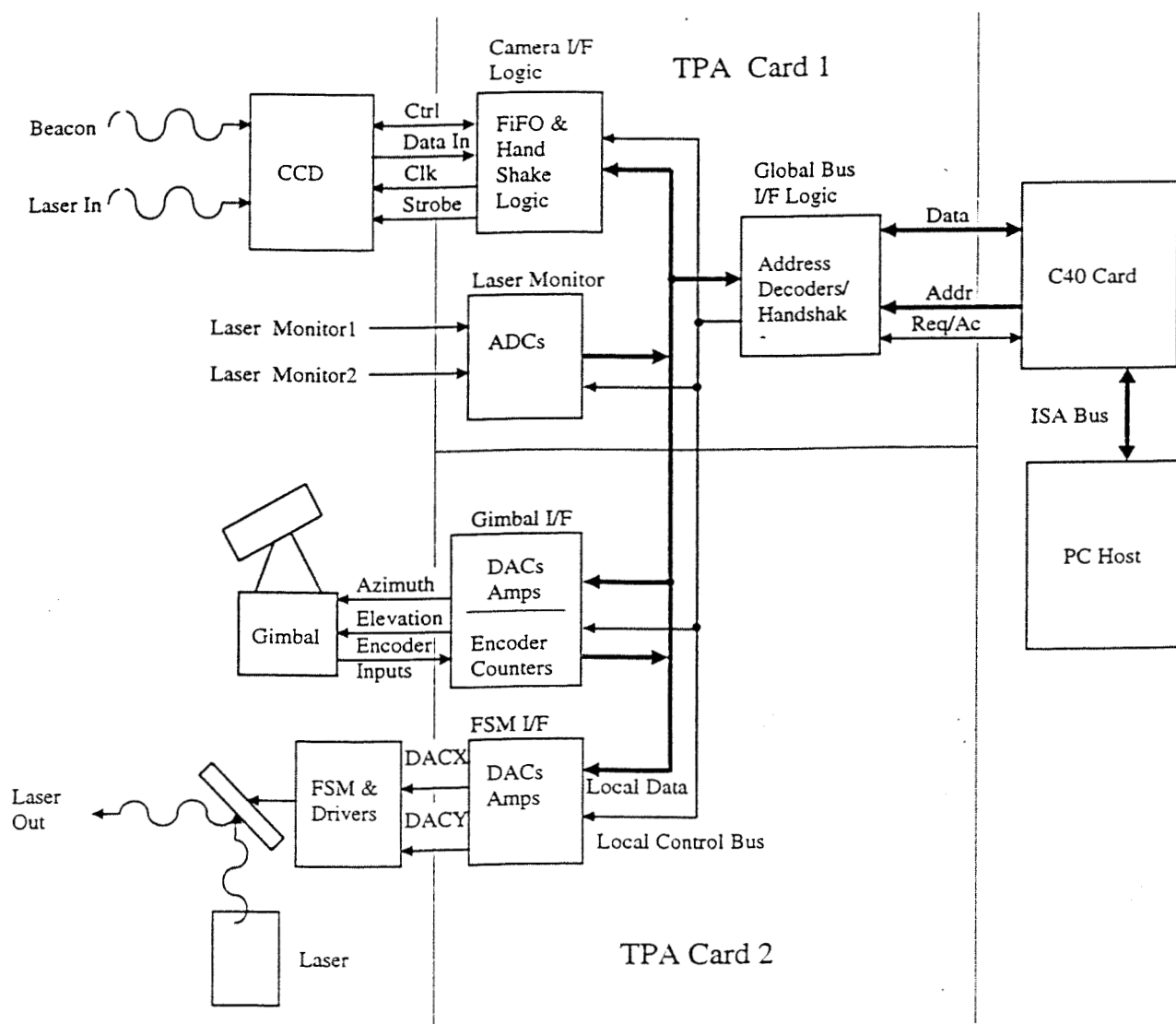


Figure 5. Functional block diagram of the two TPA cards.

diagram of OCD's PC/104 electronics design is shown in Figure 4. A 486/586 based processor is the main instrument controller. It accepts commands from and sends status information to the bus controller (BC) through the MIL-STD-1553B card. The C44 DSP card is a slave to the x86 computer and performs all the acquisition and tracking related processing. Note that the C44 is a surface-mount version of the C44 chip. Table 2 lists the manufacturers and models of the various PC/104 cards used in the OCD.

The custom TPA card had to be redesigned and split into two cards to fit to the PC/104 stack. Functional components of each of the TPA boards are shown in Figure 5. The redesign also gave us the opportunity to add some features to the original design. TPA card 1 provides the interface to the C44 DSP card through the global bus. The global bus has a pair of dedicated request/acknowledge lines used for handshaking with devices on this bus. The global bus interface on TPA card 1 consists of drivers for the address and data buses and the address decoding logic for selecting individual components on either TPA card. Additionally, TPA card 1 contains the CCD

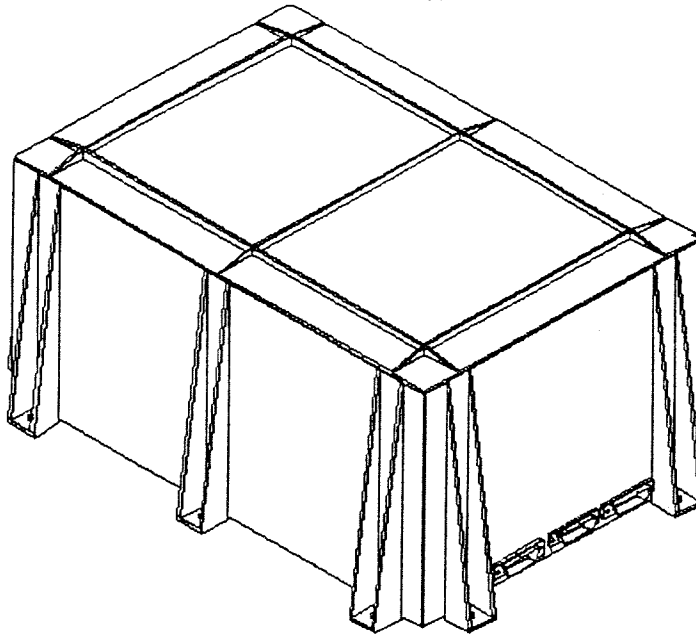


Figure 6. Sketch of the planned electronics enclosure. The dimensions of the box are 12 in x 8 in x 6 in.

camera interface logic and the laser monitor logic. TPA card 2 provides the interface logic for the FSM and gimbal control. Control of both the FSM and gimbal consist of applying analog voltages from -10 to +10 volts as positioning information for the two axis of motion of these devices. In order to avoid spurious responses by the FSM and gimbal on system power up, analog switches were placed in the control paths to decouple the DAC outputs until they are initialized. Furthermore, TPA card 2 has the counters needed to maintain the gimbal azimuth and elevation encoder positions. The counters are updated by the quadrature signals from the gimbal interpolators.

The PCB layout of the TPA cards was done in house using the PADs layout software. Each of the two PC104 cards is a 13-layer printed circuit board (PCB). The layers consist of seven signal layers, one +5 volt layer, two digital ground layers, one +15 volt layer, one -15 volt layer, and one analog ground layer. The layers were organized such that each signal layer is interleaved with a power or a ground layer to reduce crosstalk between signal layers. The two ground layers are electrically connected to the four mounting holes in the PC104 specification to provide a thermal path to the chassis for heat dissipation in a vacuum. The two card assembly has been successfully tested in a laboratory environment, but more testing will be needed to validate the design for a flight environment.

We are currently designing an electronics enclosure to house the PC/104 stack, power conditioners, Gimbal motor amplifiers and encoder electronics. The enclosure provides physical support and shielding for the elements listed above. The housing walls are flight like in fit and structure. For now, the enclosure is air cooled as this unit will be used in ground-ground and air-ground demonstrations. Space flight versions of this box will be cooled by conduction/radiation.

4. ACQ/TRK SOFTWARE

The acquisition software scans the 128x128 CCD camera image by using a 5x15 windowing scheme to locate the beacon position in the CCD field of view. The FSM is held fixed during acquisition. The scan starts at the bottom right of the CCD field of view. If a beacon is not found then the next 5x15 window directly above is scanned. This process is continued until the top of the CCD field of view is reached and is denoted as a stripe. If the beacon is still not found, the processing continues to the left to begin a new stripe. A valid beacon is defined as one or more pixels having a value greater than a predefined threshold. The transmit laser is turned off during the acquisition process so as not to confuse the acquisition algorithm. Once a valid beacon is found the software then enters the tracking mode and the transmit laser is turned on.

During tracking, a centroiding routine provides sub-pixel information on the location of the beacon and transmit laser positions in the CCD field of view. This information is used to control the FSM and gimbal as well as adjust

the active windows to be scanned on the next pass. During tracking, the CCD dumps all pixel values except from two 8x8 windows around the laser and beacon spot to achieve a frame rate of 2 kHz. The function of the tracking routine is to maintain the transmit beam at a fixed position relative to the beacon using the FSM and keep the transmit beam in the center of the CCD using the gimbal. Recently, the tracking software was modified to utilize one of the C40 timers to interrupt the C40 every 500 μ s to close the tracking loop. The foreground tracking software's main purpose is to verify the OCD has not fallen out of the tracking mode. The background process, i.e., the 500 μ s Timer Interrupt Service Routine (TISR), updates the status of the mirror and gimbal by using results calculated from the centroiding routine to calculate mirror and gimbal control signals.

The mirror error signal, which is used for controlling the fine steering mirror, is derived from the current transmit laser position, current beacon position and the desired laser position. The error signals are fed to two single bi-quadratic digital IIR filters for both the horizontal and vertical directions. The output of the digital filters is then converted to voltages and applied to the mirror axes to update the mirror position every 500 μ s. Analysis of the pointing control loop indicates that with a loop delay of 500 μ s and a centroid update rate of 2 kHz, an rms pointing error of less than 1.2 μ rad can be achieved. Furthermore, the control loop is expected to have a gain margin greater than 4 dB and a phase margin greater than 53 degrees [12].

5. SUMMARY

We intend to continue with the OCD acq/trk performance characterization over the next several months and optimize the performance where possible. Tests to be performed include characterization of the tracking bandwidth, jitter suppression, point-ahead angle implementation and accuracy, acquisition and reacquisition times, and overall communications modulation performance.

By the first half of 1998, we plan to complete the electronics packaging such that the OCD is compact self-contained unit that has just three external connections - one to a 28 V (5 A) power supply; a MIL-STD-1553B interface to a bus controller; and a high-speed ECL data channel for the transmitter. Following that, a ground-to-ground demonstration will be carried out with the OCD placed at Strawberry Peak and a receiver located at Table Mountain Facility (near Wrightwood, CA). We will also prepare for an air-ground demonstration in late 1998 or early-1999 with the OCD on an aircraft. Results from OCD characterization, the demonstrations, and environmental testing will be used to improve and construct another optical communication terminal that can be used for space-to-ground links.

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